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UTILITY PATENT APPLICATION

FOR

MODEL-BASED FAULT DETECTION IN A MOTOR DRIVE

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MODEL-BASED FAULT DETECTION IN A MOTOR DRIVE

Technical Field

The present invention pertains to a method for detecting a fault condition in a motor, such as open motor winding, using residue voltage differences and other passive measures.

Background of the Invention

Dynamically stabilized transporters refer to personal vehicles having a motion control system that actively maintains the stability of the transporter while the transporter is operating. The motion control system maintains the stability of the transporter by continuously sensing the orientation of the transporter, determining the corrective action to maintain stability, and commanding the wheel motors to make the corrective action. If the transporter loses the ability to maintain stability, the rider may experience discomfort at the sudden loss of balance. The risk of such discomfort may be reduced if redundant components are provided in the transporter drive train. For example, providing dual-stators in the motor driving the transporter's ground contacting elements (e.g., wheels) reduces likelihood of loss of balance. When redundant components are provided, a method for detecting failure of a redundant component is desirable so that a failed component may be replaced before a double failure occurs.

Active detection of an open motor winding, namely a periodic attempt to force current into the motor to distinguish between a normal motor and one with an open winding, may not be feasible without requiring the motion control system to give up some control over the motor's torque production. A method for passively monitoring motor winding circuits to determine open circuit conditions would advantageously allow such open circuits to be detected without disturbing motor operation.

Summary of the Invention

In an embodiment of the present invention, a method is provided for detecting an open winding in a motor. The method employs passive monitoring of the voltage, current and speed of the motor. A residue voltage is calculated that equals the difference between an idealized set of voltage drops across the motor load elements and the actual voltage drops. When the magnitude of the residue voltage equals or exceeds a threshold, an open winding condition may be declared and appropriate action may be taken.

In another embodiment of the invention, a dual-stator redundant motor is provided. The method employs passive monitoring of the voltage, current and speed of the motor for each of the dual-stators of the motor. Residue voltages are calculated for each stator that measure the difference between an idealized set of voltage drops across the respective motor load elements and the actual voltage drops. When the magnitude of the difference of these two residue voltages equals or exceeds a threshold, an open winding condition may be declared and appropriate action may be taken. In a further embodiment of the invention, an open winding may be declared when either the condition on the difference of the residues is met or when the magnitude of either of the residues of the individual-stators equals or exceeds a threshold. In each of these embodiments, an open motor winding or other causes of an open winding circuit, such as an open relay, a broken wire or an open fuse link may be detected.

Brief Description of the Drawings

The foregoing features of the invention will be more readily understood by reference to the following detailed description, taken with reference to the accompanying drawings, in which:

Fig. 1 is a side view of a personal vehicle lacking a stable static position, for supporting or conveying a subject who remains in a standing position thereon;

Fig. 2 shows a block diagram of the system architecture of an embodiment of the present invention;

Fig. 3 is a block diagram for an algorithm for detecting opening windings in a dual-stator redundant motor according to an embodiment of the invention;

Fig. 4 is a block diagram of an exemplary reference transform according to an embodiment of the invention; and

Figs. 5A-5D illustrate filter lag compensation.

Detailed Description of Specific Embodiments

The subject matter of this application is related to U.S. Patent Nos. 5,701,965; 5,971,091; 5,791,425; 6,302,230 and U.S. Patent Application, serial no. 09/687,789, attorney's docket 1062/C40, "Transporter Improvements," filed October 13, 2000, which are all incorporated herein by reference in their entirety.

In an embodiment of the present invention, a method is provided for detecting an open winding in a motor. The method employs passive monitoring of the voltage, current and speed (or equivalently rotational frequency) of the motor. A residue voltage is calculated that equals the difference between an idealized set of voltage drops across the motor load elements and the actual voltage drops. When the magnitude of the residue voltage equals or exceeds a threshold, an open winding condition may be declared and appropriate action may be taken.

In another embodiment of the invention, a dual-stator redundant motor is provided. The method employs passive monitoring of the voltage, current and speed of the motor for each of the dual-stators of the motor. Residue voltages are calculated for each stator that measure the difference between an idealized set of voltage drops across the respective motor load elements and the actual voltage drops. When the magnitude of the difference of these two residue voltages equals or exceeds a threshold, an open winding may be declared and appropriate action may be taken. In a further embodiment of the invention, an open winding condition may be declared when either the condition on the difference of the residues is met or when the magnitude of either of the residues of the individual-stators equals or exceeds a threshold. In each of these embodiments, an open motor winding or another cause of an open circuit, such as an open relay, may be detected.

Embodiments of the present invention will be described for a dynamically balancing transporter. These embodiments are presented by way of illustration and not for limiting the scope of the invention as described by the appended claims. As those skilled in the art will

recognize, the present invention may be used in any device where detection of an open winding circuit is desired.

Dynamically-Balancing Transporter

A personal transporter may be said to act as dynamically 'balancing' if it is capable of operation on one or more wheels but would be unable to stand on the wheels but for operation of a control loop governing operation of the wheels. A balancing personal transporter lacks static stability but is dynamically balanced.

An embodiment of a balancing personal transporter is depicted in Fig. 1 and designated generally by numeral **10.** User **8** is shown in Fig. 1, standing on platform (or 'base') **12** of ground-contacting module **26**. Wheels **20** and **21** are shown as coaxial about the **Y** axis. A handlebar **14** may be provided on stalk **16** for gripping by the user.

Referring now to Fig. 2, a block diagram is shown of a system architecture for an embodiment of the present invention. This block diagram shows the architecture for controlling and driving one wheel **20** of transporter **10**. An analogous block diagram applies to controlling and driving the other wheel **21** of the transporter. A motor **120** drives wheel **20** of the transporter. The motor **120** is preferably DC brushless, but may be either AC or DC motors and either brushed or brushless. The motor **120** is energized by a redundant set of windings **121**, **122**. Both windings are capable of energizing the motor either independently or simultaneously. Motor **120** has a sensor **123** that measures the position or angular velocity of the motor shaft. Conversion of a signal representing instantaneous shaft velocity to or from a signal representing position is accomplished by integrating or differentiating the signal, respectively.

Processor **135** monitors various parameters of each winding **121, 122** via sensors **137, 147** that monitor at least the voltage and current for each winding. Processor **135** controls the voltage or current applied to each winding via the A winding motor drive **133** and the B winding motor drive **143.** The A winding motor drive **133** derives power from the A power supply **131** and the B winding motor drive derives power from the B power supply **141**.

Open Winding Detection

A method is described below for detecting an open winding in a motor **120** according to an embodiment of the invention. By way of example, but not for limitation, this method may be performed using a computer processor, such as processor **135** in the architecture described above.

This method assumes that:

1. The electrical relationship between motor terminal voltage, current, and motor speed is approximately known under normal circumstances, and changes in the case of an open winding.
2. In a system containing a motor with a dual - redundant winding, at most one of the two stators will contain an open winding. Further, the electrical parameters of the motor (e.g., back-EMF constant Ke, resistance R, and inductance L) will be reasonably matched between the two half-motors.

A quantity, which will be called the "residue voltage" in this specification and in any appended claims, can be calculated by subtracting estimated values of the components that make up motor voltage, i.e., back-EMF and IR voltage drops, from the measured value of the motor voltage itself. The residue voltage effectively compares the actual value of motor voltage to its expected value during normal operation. A large residue voltage may indicate the presence of a fault condition, which could be due to an open winding or an open relay or another open component in the winding circuit. The term "open winding condition" in this specification and in any appended claims will be understood to mean an open winding or another cause of an open circuit in the motor. Further, "open winding condition" will also include: improper measurement of motor voltage, current and/or speed or a mismatch between motor parameters and their estimated values. Ideally, when there is no open winding condition, this residue voltage should always be zero. Some assumptions about the motor resistance and back EMF constant must be made to calculate these voltage drops and precise measurements of motor voltage, current and frequency must be obtained. In reality, these ideal conditions do not occur so errors present in these numbers can produce significant residue levels. An analysis of these errors is presented in Appendix A. Further, in this embodiment of the invention, the measurements of motor speed, current and voltage

are all filtered at different frequencies, contributing to a non-zero residue voltage even with no open winding condition. Therefore, data acquisition filter lags are accounted for in the residue calculation, as described in Appendix B. Under these assumptions, it is possible to observe an open winding passively (in other words without requiring any changes to motor commands), when the torque commanded is sufficiently large to produce an observable effect.

For a DC motor, the following equation holds:

$$V = K_e \cdot \omega_m + I \cdot R + L \frac{dI}{dt}$$

where:

V is the voltage across the motor,

K_e is the back-EMF constant of the motor,

ω_m is the mechanical speed of the motor,

I is the current through the motor,

R is the motor winding resistance, and

L is the motor winding inductance.

Under steady-state operation, $L \frac{dI}{dt}$ is approximately zero and a residue, r, can be calculated.

$$r = V - K_e \cdot \omega_m - I \cdot R$$

where V, I, and ω_m are measured quantities and K_e and R are estimates of motor parameters.

If r is approximately zero, then the relationship between measured motor voltage, current and speed matches what is expected and the motor can be assumed to be operating normally.

If r is non-zero, it may indicate that a fault (an open winding condition) has occurred. Such faults may include:

- an open winding or broken wire has occurred;
- voltage, current and/or speed may be measured improperly; or
- motor parameters K_e and R do not match their estimated values.

Similar equations hold true for a three-phase permanent magnet synchronous motor ("PMSM").

In the synchronous (rotor) reference frame of a PMSM, the following equations hold when no open winding condition is present:

$$V_{qLN} = K_{eLN} \cdot \omega_m + I_q \cdot R_{LN} + I_d \cdot \omega_e \cdot L_{LN} + L_{LN} \frac{dIq}{dt}$$

$$V_{dLN} = I_d \cdot R_{LN} - I_q \cdot \omega_e \cdot L_{LN} + L_{LN} \frac{dI_d}{dt}$$

where:

the subscript "LN" denotes line-neutral quantities;

"d" refers to the direct-axis of the synchronous reference frame, where currents are non-torque producing and voltages are out of phase with back-EMF;

"q" refers to the quadrature-axis of the synchronous reference frame, where currents are torque producing and voltages are in- phase with back-EMF;

K_{eLN} is the motor's back-EMF constant;

I_q and I_d are the synchronous-frame components of motor current;

V_{qLN} and V_{dLN} are the synchronous-frame components of line-neutral motor voltage;

R_{LN} is the line-neutral resistance;

L_{LN} is the line-neutral inductance;

ω_m is the mechanical speed of the motor;

ω_e is the electrical frequency, equal to p/2 times ω_m, where p is the number of motor poles;

d( )/dt is differentiation with respect to time.

For the steady state case where $\frac{dI_q}{dt}$ and $\frac{dI_d}{dt}$ are zero, a residue voltage, r_q, may be calculated where:

$$r_q = V_{qLN} - I_q \cdot R_{LN} - K_{eLN} \cdot \omega_m - I_d \cdot \omega_m \cdot L_{LN},$$

where V_{qLN}, I_q, I_d and ω_m are derived from measurements, while R_{LN} and K_{eLN} are estimated. r_q has units of volts, line-to-neutral. Note that if I_d is controlled to zero, then the last term in the preceding equation can be ignored.

When no open winding condition is present, r_q is approximately zero.

When there is either an entire set of open windings or a single open winding, the residue voltage, r_q tends to be non-zero for either of two cases:

1. When the motor is commanded in a <u>voltage mode</u> and when the commanded V_{qLN} differs from the internal back-EMF, $K_{eLN} \cdot \omega_m$, i.e. current would flow in a normal motor but cannot due to the open winding; or
2. when the motor is commanded in a <u>current mode</u> and the current commanded is non zero.

In either of these cases, the residue of a system with an open winding begins to diverge from zero (the expected residue for a normal system), and the open winding can be detected. Current mode motor commands tend to produce larger residues because the motor drive is actively trying to force current through the motor, and in the case of an open winding, V_{qLN} becomes very large (at all times in the case of an open winding set, and at various times depending on the speed and electrical angle for a single open winding in a winding set). In voltage mode V_{qLN} becomes only as large as its command (with some torque ripple in a motor with a single open winding, because this is an unbalanced load).

In practice, the residue voltage can be compensated for differences in the time delays that are introduced by analog low-pass-filters on the voltage, current, and speed sensor inputs, by calculating the residue in the following manner:

$$r_q = V_{qLN} - I_q \cdot R_{LN} + (K_d \cdot V_{dLN} - K_{eLN}) \cdot \omega_m$$

where $K_d \approx \frac{p}{2} \cdot \Delta\tau$ $\quad$ p = number of motor poles

$\Delta\tau$ = time delay, between position and voltage sense.

Such compensation greatly improves the accuracy of detection. The derivation for this equation is discussed in Appendix B.

Calculation of the residue voltage, r_q, provides a test that can be used in a motor drive, regardless of whether it is in a single-stator motor or a dual-stator redundant motor, namely:

$$B_{ow} = \left(\left|LPF\left(r_q\right)\right| > R_{THRESH}\right),$$

where B_{OW} is a Boolean value that represents whether an open winding condition has been detected and "LPF" means that the value of r_q has been filtered with a low-pass filter. The low-pass filter's cutoff frequency should be a compromise between rejecting high-frequency errors and a sufficiently rapid detection. A value of $\approx$ 1.5Hz has been used advantageously in a dynamically balancing transporter.

In a system with a dual-stator redundant motor, two residues r_{qA} and r_{qB} may be calculated. A second test that can be then applied is:

$$B_{ow\_AB} = \left(\left|LPF\left(r_{qA}\right) - LPF\left(r_{qB}\right)\right| > R_{THRESH\_AB}\right),$$

where B_{ow_AB} is also a Boolean value that represents whether an open winding condition has been detected.

The system can use both bits, namely, if

$(B_{ow}=TRUE)$ or $(B_{ow\_AB}=TRUE)$

then an open winding condition is detected: take appropriate action.

If both halves of the redundant motor are driven with similar voltage commands, then B_{ow_AB} is more sensitive in detecting open windings than B_{ow} alone, because some of the errors listed in Appendix A cancel out partially or completely.

Note, however, that calculating B_{ow_AB} requires some communication between the two motor drives controlling current into the two stators, A and B. Further, r_{qA} and r_{qB} used in the above equation should correspond to the same instant in time, so that if side A gets r_{qB} with a delay, the same delay should be incorporated in its own residue, r_{qA}, before subtracting the two residues.

A block diagram for the algorithm for this embodiment of the invention is depicted in fig. 3. Typical values of update rate are shown for the various blocks. First, the residue

voltage, r_q, is calculated **310**. This voltage is run through a low-pass filter **320** and then sampled **330** at a 100 Hz rate. The filtered value of r_q **340** is passed as an input to a corresponding algorithm for the other stator. The difference in time between the values of r_q for each side is compensated **350** and a voltage difference is formed **360.** Finally, the voltage difference is compared to the threshold **370.**

Motor Measurements

Voltages V_q and V_d and currents I_q and I_d are used in synchronous-frame control algorithms for three-phase motor drives: phase voltages and currents, which oscillate at the motor's electrical frequency, are changed to DC or slowly-varying quantities which can be more easily controlled with zero steady-state error.

A block diagram of an exemplary reference transform is shown in fig. 4

Referring to fig. 4, where V_a, V_b, V_c are measured motor phase voltages and θ_e is an electrical angle derived from a position sensor (e.g. resolver, encoder, etc.), the "abc/xy" and "xy/dq" blocks function as follows:

$V_x = 2/3\ V_a - 1/3\ V_b - 1/3\ V_c$;

$V_y = 1/\sqrt{3}\ (V_b - V_c)$;

$V_d = V_x \sin(\theta_e) - V_y \cos(\theta_e)$; and

$V_q = V_x \cos(\theta_e) + V_y \sin(\theta_e)$.

Equivalent formulations of these equations will be apparent to those skilled in the art. All formulations have the property that if

$V_a = A \cos(\theta_e) + B \sin(\theta_e) + C$;

$V_b = A \cos(\theta_e - 120^\circ) + B \sin(\theta_e - 120^\circ) + C$; and

$V_c = A \cos(\theta_e - 240^\circ) + B \sin(\theta_e - 120^\circ) + C$.

then the transformation yields $V_q = A$ and $V_d = B$ (or $V_q = -B$ and $V_d = A$ in some formulations). Thus, a three-phase set of oscillating waveforms is transformed into a pair of DC values which are sufficient to describe the magnitude and phase of the original signals.

The same transform equations may be used to calculate I_d and I_q from phase currents I_a, I_b, and I_c.

It should be understood that measuring voltages V_q and V_d and currents I_q and I_d implies deriving them from measured phase voltages and currents and measured motor positions. Likewise, in this specification and in any appended claims, unless context requires otherwise, "measuring a speed" includes direct speed measurement or taking a series of position measurements with associated times and then calculating a speed.

Algorithm Initialization

The residue voltage filters need to be zeroed after a sufficient interval has elapsed after transporter startup. For a dual-stator motor, the algorithm results may be ignored until the remote data communication busses described in connection with fig. 2 have been synchronized. The response to the algorithm may be disabled for a fixed delay, such as 250 milliseconds, after this initialization as added insurance against a false positive at start-up. The primary issue is that until the filters on both sides are zeroed, the delta residue can be quite large, especially if one side has been zeroed and the other has not yet. The transport delay between the two sides can further complicate matters. The one-time 250 ms suppression of the response to the algorithm at startup more than adequately addresses this concern.

The described embodiments of the invention are intended to be merely exemplary and numerous variations and modifications will be apparent to those skilled in the art. All such variations and modifications are intended to be within the scope of the present invention as defined in the appended claims.